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The Development and Field Testing of a Less Hazardous and Technically Superior Oil Based Drilling Fluid

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Abstract

This paper describes the development and subsequent field results of a new invert emulsion, low toxicity, oil based drilling fluid (LTOBM). The new fluid was developed in response to the anticipated increased usage of LTOBM, and primary considerations in the development were those of working conditions, the environment, technical performance and economics.

Developments in invert emulsion drilling fluids have, over recent years, been concentrated in the areas of reducing environmental impact, and improving technical performance. LTOBM have, as a result of this, been largely replaced by synthetic based drilling fluids (SBM), which exhibit similar, or improved technical performance, whilst claiming to have reduced environmental impact. This development focus has resulted in very few changes being made to LTOBM since the replacement of diesel by low toxicity mineral oil.

The occupational health hazards involved in using SBM have, however, proven to be similar, or occasionally worse, than with LTOBM. Such health problems can be mainly attributed to two components; the base fluid and lime, the latter being a major contributor to skin irritation problems, and the former to both skin irritation, and inhalation problems. There has been a lack of occupational health studies carried out with respect to the use of SBM compared to LTOBM.

This paper describes the laboratory testing conducted, and results obtained during the development, where several base fluids were screened, along with a multitude of fluid additives, prior to obtaining the optimal formulation. The final fluid was designed for use on high temperature high pressure wells and extended reach wells, as well as more "normal wells". The laboratory data presented is supported by field data from the successful use of the system as a worker friendly, high performance, LTOBM drilling fluid.

Introduction

Invert emulsion drilling fluids are the preferred fluid for many wells in Norway and worldwide[1,2,3]. This is as a direct result of their technical and economic performance. Water based drilling fluids have not yet been able to obtain the same performance with regard to wellbore stability, lubricity and drilling rate. Thus invert emulsion fluids continue to be used.

Developments in invert emulsion drilling fluids have focused on the development of various synthetic based drilling fluids. Restrictions are present in Norway for the discharge on cuttings of these fluids. The development of cuttings injection technology[4,5,6] has led in many cases to low toxicity oil based drilling fluids being the optimal fluid choice. Concerns for the working environment together with a desire for a technically superior LTOBM led to the setting up of a project.

Project Goals

The project team, composed of representatives for the LTOBM supplier and the oil company, agreed upon the following project goals, given in order of importance:

1) Provide a working environment superior to present LTOBM.
2) Improve upon the technical performance of current LTOBM.
3) Improve upon the marine toxicity of current LTOBM.
4) Ensure that the new fluid costs are acceptable.

The project was to examine both the additives and the base fluid for the LTOBM.

General Health Evaluation of the Base Oils

Qualitative analysis of vapour originating from the use of oil based mud on the drill floor and in the mud area, show that more than 90 % of it originates from the base oil[7-10]. The main constituents in low aromatic base oils are, as shown in Table 1,

Paraffins, Aromatics and Naphthenic hydrocarbons. Previous experiments have shown[11-13] that when equal concentrations of paraffinic, naphthenic and aromatic vapour are inhaled, more aromatics appear in the human and animal blood. This is due to lower solubility in the blood of naphthenic and paraffinic hydrocarbons. However, a study performed by Statoil[14] has shown that the concentration of naphthenes in the brain is approximately twice that of aromatics after inhalation of air containing equal amounts of such hydrocarbons. Thus, it is therefore uncertain whether a change from low aromatic mineral oil to one containing an increased amount of naphthenes is of a beneficial nature.

Samples of and data on nineteen different base oil were obtained from suppliers. Some of the base oils are currently in use worldwide ,whilst others were new to the market. An initial screening process was carried out based on the technical data received from the suppliers. The following parameters were evaluated in the initial screening process:

1. Aromatic content — as low as possible and less than 4%
2. Viscosity — low to middle
3. Flash point — as high as possible over 100°C
4. Vapour pressure — as low as possible
5. Aniline point — as high as possible
6. Sulphur content — as low as possible
7. Boiling point — initial as high as possible, final as low as possible

The chemical analysis results of the six base oils remaining after the screening process can be seen in Table 1. The analysis has been conducted using GC-MS. The GC-MS values obtained gave consistently higher aromatic values than the values obtained by the more accurate (for aromatics) UV technique.

The aromatic content of base oil E is lower than any of the other oils tested. The total aromatic content of base oil E was 0.78 %. The base oil currently in use today on the Norwegian sector is base oil C. This base oil has the highest total aromatic content of the remaining base oils from the screening process with 5.84 %. Table 1 also shows that base oil E contains a lower amount of naphthenes (43.4 %) compared to base oil C (46.6 %). Thus, a replacement of base oil C with base oil E should therefore be beneficial with regard to the effect on the brain following inhalation.

The paraffinic content of base oil E (55.8 %) is higher than that of base oil C (47.1 %). The paraffins are, however, in the C_{10} - C_{32} range and most of the studies performed[15-18] on rats have shown that behavioural changes such as aggression only occurs in the C_8 - C_{10} range. The drill floor and the shale shakers are areas where most of the mist and vapour from the drilling fluids will be experienced. However, qualitative analysis of vapour from low-aromatic oil based drilling fluids have shown that greater than 90 % comes from the base oil.

The vapour pressure of the selected base oil should be as low as possible in order to experience the lowest vapour content in the air at elevated temperatures[19]. Figure 1 shows the results obtained from the vapour pressure testing. Base oils D and E display the best characteristics. The differentiation between these two base oils and the remaining three is clearly defined in terms of vapour pressure.

Skin and Eye Irritation Evaluation of Five Base Oils

Table 2 includes skin irritation test results for five of the base oils remaining after the screening process described above.

None of the oils inflicted any inflammation of the eyes of the rabbits tested and the skin irritation tests for Oedema and Erythema showed an effect only for Erythema. Table 2 shows that the Erythema values for skin irritation varied between 0.2 and 1.0 for the base oils tested. It is again base oil E which yields the best results with only 0.2 for Erythema. Any product with an average Erythema and Oedema score greater than 2 will be classified as a skin irritant. Thus, none of these base oils can be categorised as such.

Marine Toxicity Evaluation of the Five Base Oils

Table two includes test results for marine toxicity test performed on the five base oils discussed above.

Both *Mytilus edulis* and *Abra alba* are test species which are known to be sensitive to the toxicity of base oils and oil based drilling fluid systems and were therefore selected as appropriate test organisms for the toxicity evaluation. It can be seen that the results obtained for *Mytilus edulis* are all rather low and difficult to differentiate between. The difference in results is assumed to be insignificant and probably within the experimental error range. Thus, more emphasis has been placed on the *Abra alba* results. Base oil E is clearly the least toxic of the base oils tested (16 -58 times less than the others).

Environmental Evaluation of the New Oil Based Drilling Fluid

Base oil E has shown an overall superiority in all the environmental and health tests conducted and it was therefore decided to have this base oil tested for the remaining Parcom / SFT organisms. The test results can be found in Table 3, and show that base oil E displays less toxic behaviour than the one currently in use today (C), both towards the water soluble sensitive algae *Skeletonema costatum* and towards the non-water soluble sensitive organism *Abra alba*. Base oil E and the new oil based system comprising this base oil should therefore satisfy the Norwegian environmental regulations regarding accidental discharge. These state that it is the operator's responsibility to ensure that any new mineral oil based drilling fluid system to be introduced should be more environmentally friendly than the oil based systems in use today.

The following pass criteria have been issued by the Norwegian Environmental Authority (SFT) in terms of toxicity testing of drilling fluids:

Skeletonema costatum	EC50	> 1,000 mg/l
Acartia tonsa	LC50	> 2,000 mg/l
Abra alba	EC50	> 20 mg/kg
Mytilus edulis	LC50	> 1 mg/kg
Corophium volutator	LC50	> 1,000 mg/kg

Although oil based drilling fluid contaminated cuttings are not allowed to be discharged, there is a possibility that accidental spills might occur. Base oil E was therefor tested for aerobic biodegradation, as this information could be useful if any future accidental spills occurred. Base oil E and base oil C degrade well aerobically. As seawater contains oxygen it is likely that lesser accidental spills will not cause environmental havoc. Anaerobic biodegradation was not tested as the current LTOBM exhibits zero anaerobic biodegradation and the new LTOBM's performance could not therefor be any worse.

Skin Irritation Evaluation of the New Oil Based Drilling Fluid

Skin irritation test results for the new LTOBM are included in Table 3. The skin irritation results show that base oil E has better skin irritation properties than the old base oil C in terms of Erythema, as discussed previously. The average Erythema/Oedema score for the new oil based system with the new base oil E is 0.77. This is a significantly lower value than the average score obtained for the new system with the old base oil (C), which is 1.1. However, none of these laboratory drilling fluids can be classified as "skin irritants" as the average erythema and oedema values are less than 2. The average value obtained for the old oil based drilling fluid system was 1.65 and is significantly higher, thus the old system is more likely to contribute to skin reactions if personnel come in direct contract with this drilling fluid.

The skin irritation potential obtained for the new oil based system (with the new base oil E) can be better appreciated when it is compared to values obtained for other commonly used drilling fluid systems (Table 4).

Ecetox (1995)[20] have suggested a formula for ranking irritating chemicals called PII: Primary Irritation Index. The values for the right and left test areas on each rabbit are averaged and the total sum of the influences is divided with the number of observations (4) after 1, 24, 48 and 72 hours. The score for each rabbit is then summarised and divided by the number of rabbits used in the test.

It is an interesting fact that a standard KCl/Polymer mud is approximately 40 % more likely to inflict skin irritation than the new oil based system containing base oil E. The least damaging drilling fluid system ever tested (by the involved companies) is a new water based drilling fluid system. This is a water based system using Na-Silicate as a shale inhibitor. The skin irritation results obtained for this system (0.08) is rather unexpected, as the pH of the system is greater than 11.

Table 4 shows that the new oil based drilling fluid system using base oil E displays the lowest PII index of all the synthetic and oil based drilling fluid systems tested. This is surprising as the content of lime in a synthetic or oil based drilling fluid system will normally contribute additionally to skin irritation. The new oil based drilling fluid system does contain lime, but the fish oil ester system does not and it would therefore have been expected for the ester system to have displayed better skin irritation characteristics. Thus, it is plausible to conclude that the new oil based drilling fluid system (with base oil E) is the least skin irritating drilling fluid system of all emulsion systems on the market today.

Technical Performance

The primary goals for the technical performance of the fluid were stability to at least 185°C and improved rheological characteristics compared to the LTOBM in use. Figure 2 and Figure 3 illustrate the rheological parameters for the earlier LTOBM (LTOBM 1) and the new LTOBM (LTOBM 2). The laboratory data in Figure 2 was replicated under field conditions shown in Figure 3. As can be seen the new fluid has a flatter rheological profile than the earlier fluid. This leads to advantages such as lower circulating pressures and lower Equivalent Circulating Density (ECD). At the same time the fluid has a similar Fann 3 rpm reading. This was thought to be desirable due to the connection between this value and both barite sag[21,22] and hole cleaning[22].

The earlier LTOBM was not stable over 150°C. At this temperature filtration control was lost and the rheology became unstable. As it was planned to use the new fluid at temperatures up to 175°C, the new system required temperature stability up to 185°C. An extensive suite of tests were carried out in order to arrive at the optimal drilling fluid formulation. This included testing the various products at temperatures up to 200°C and for resistance to contamination by seawater, cement and simulated drill solids. This testing lead to an optimal fluid formulation. Table 5 shows some of the test results.

Laboratory tests were carried out comparing the friction factor of the new LTOBM to that of the old LTOBM. These tests showed that the factors were similar. This has been confirmed by field data.

Based on the above laboratory testing the new LTOBM was considered to be technically qualified for field use.

Field Trials

To date the new LTOBM has been used on fifteen wells and is planned for future wells requiring LTOBM. The system as used to date has not used the new base oil for contractual reasons, but it is expected to become the standard base oil in the near future. The new LTOBM has been used on a variety of wells with hole angles varying from vertical to horizontal and with bottom hole

temperatures up to 175°C. The introduction of the new system has been carried out partly by the replacement of the original products with the new products and partly by the mixing of total volumes of the new LTOBM.

There have been no negative experiences associated with the introduction of the new LTOBM. Table 6 shows drilling fluid properties for wells drilled with the old and new fluids. The changes in properties are all seen as positive. The viscosity profile is superior with the new system, leading to lower circulating pressures. These improvements in the viscosity profile are attributed to the new emulsifier package. No barite sag has been experienced with the new system, whereas this was not an uncommon problem with the old system, when treatment of the Plastic Viscosity could result in barite sag. Barite sag is a complicated subject and accordingly it is difficult to explain the improvement. The new LTOBM's viscosity profile enables a lower Plastic Viscosity to be maintained without compromising the low shear rate viscosity and yield stress values, which experience have been shown to reduce the risk of barite sag[21,22].

Overall Evaluation

This project has evaluated 19 base oils in terms of environmental, health and technical properties. The new, selected base oil E displays superior properties in all environmental and health tests conducted, particularly with respect to toxicity and skin irritation. Both the naphthenic and aromatic content of base oil E are less than that found in base oil C, the base oil currently in use. This is regarded as favourable with respect to inhalation. Particular emphasis has been placed on the aromatic content of the evaluated base oils. The aromatic content of base oil E is 10 ppm, compared to the one currently in use which is approximately 6 %.

A new oil based drilling fluid system has been developed during this project. The laboratory results show superior technical performance of this drilling fluid system in terms of temperature stability, solids and contamination properties and rheology profile, compared to the old oil based drilling fluid system, and have as such fulfilled the objective. The technical aspects of the new system have since been validated through the drilling of fifteen wells. A noticeable, positive, improvement has been observed in terms of drilling parameters. The new system has also been used to drill a well with a maximum temperature of 175°C, however, laboratory results have shown that the new fluid system will be stable to temperatures in excess of 200°C.

The skin irritation properties of the new oil based mud system are much better than the old system, and is probably the least irritating system on the market today compared to other emulsion systems. Additionally, an accidental spill of the new system is likely to inflict less damage to the environment in terms of toxicity than the old system was capable of.

Conclusion

This project has succeeded in achieving its goals. A new LTOBM has been developed which is less health damaging than the previous system and at the same time is technically superior and more environmentally friendly.

Nomenclature

PV	= Plastic Viscosity (as defined by API), mPa.s
YP	= Yield Point (as defined by API), Pa
SFT	= (Norwegian) State Pollution Authority
GC-MS	= Gas cooled mass spectrometer
UV	= Ultra-violet
EC50	= Concentration effecting 50% of the species concentration
LC50	= Lethal concentration for 50% of the species concentration

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SI Metric Conversion Factors

°F		(°F-32)/1.8		=	°C
lbf/100 ft²	x	4.788026	E-01	=	Pa
cP	x	1.0*	E-03	=	Pa.s
lbm/US gal	x	1.198264	E+02	=	g/m³
psi	x	0.689655	E-01	=	bar

Table 1 : Main constituents of six low aromatic base oils

Compound	Base oil A	Base oil B	Base oil C	Base oil D	Base oil E	Base oil F
Paraffins (C_{10} -C_{32}), %	48.5	60.1	47.1	51.4	55.8	49.7
Mono-naphthenes, %	24.3	15.5	30.1	28.8	32	24.1
Di-naphthenes, %	18.3	16.2	16.5	12.7	11.4	17.8
Mono-aromatics, %	0.56	2.21	3.21	0.33	0.05	0.16
Di-aromatics, %	1.81	1.47	2.63	4.11	0.73	1.71
Tri-aromatics, %	0	0	0	0	0	0
Dibenzothiophenes, %	0	0.01	-	0	0.01	0
Other compounds, %	6.61	4.57	-	2.74	0	6.55

Table 2 : Health and environmental test results of five base oils

Type of base oil	*Mytilus edulis* EC_{50} (ppm)	*Abra alba* LC50 mg/l	Eye irritation	*Erythema	*Oedema
A	0.09	10	0	1	0
B	0.14	26	0	0.5	0
C	0.3 - 0.4	22	0	0.6	0
D	-	36	0	0.8	0
E	-	576	0	0.2	0

* Skin irritation, OECD 404

Table 3 : Environmental and health data for the new and old oil based drilling fluid system

Base oil/ mud system	*Skeletonema costatum* EC50 mg/l	*Acartia tonsa* LC50 mg/l	*Abra alba* EC50 mg/kg	*Mytilus Edulis* EC50 mg/kg	*Corophium volutator* LC50 mg/kg	Aerobic biodegradability, %	*Erythema	*Oedema
Base oil E	> 100,000	76,088	576	--	-	60.7	0.2	0
Base oil C	-	-	22	0.3-0.4	-	64	0.6	0
New oil based mud system with Base oil E	> 100,000	23,668	290	-	2,196		1.33	0.2
New oil based mud system with Base oil C	> 100,000	21,842	92	-	-		1.6	0.6
Old oil based mud system with Base oil C	1,734	-	-	1.6	-		2.75	0.55

* Skin irritation, OECD 404

Table 4 : Primary skin irritation index for a range of drilling fluid systems and base fluids

Drilling / Base fluid	Primary Skin irritation index PII
Fresh water based Na-Silicate mud	0.08
Seawater based Na-Silicate mud	0.08
New base oil E	0.375
Fresh water based Na-Silicate mud with KCl	0.46
Old base oil C	0.667
Water based Gyp/Polymer	0.781
Water based KCl/glycol mud	1.22
Acetal base fluid	1.313
New oil based mud with base oil E	1.41
Fish oil ester based synthetic mud	1.65
LAO (14-16) base fluid	1.833
New oil based mud with old base oil (C)	2.31
LAO Based synthetic mud	2.625
Water based KCl/Polymer	2.969
Old oil based mud with base oil C	3.063
Fish oil ester base fluid	4.5

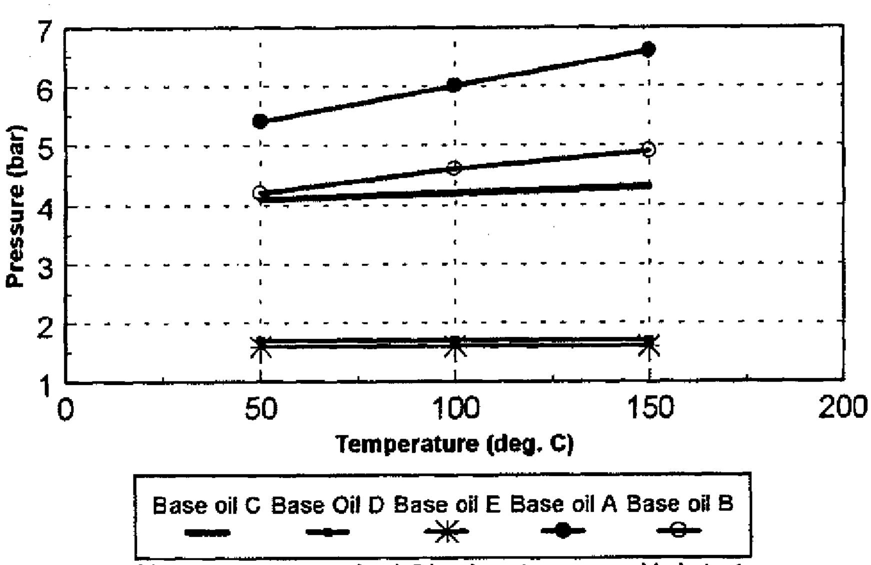
Table 5 :Drilling fluid properties of the new fluid after 16 hours dynamic ageing.

Ageing Temperature, °C	100	160	185
Density, S.G.	1.6	1.2	1.6
PV, mPa.s	22	22	40
YP, Pa	4.5	7	3.5
Fann 3 rpm reading	4	5	3
Oil/water ratio	80/20	80/20	80/20
HPHT filtrate, ml	3	4	3
HPHT @ °C	150	150	150

Table 6 : Drilling fluids properties for two production wells on the same field

Well	Well 1	Well 2
LTOBM system	Old LTOBM	new LTOBM
Density, S.G.	1.6	1.59
Fann 3 rpm dial reading	8	10
PV, mPa.s	56	40
YP, Pa	10	8.5
Electric Stability, volts	693	961
HPHT Filtrate, ml @100°C	2	1.5

Figure 1 : Vapour pressures of five base oils



* Vapour pressure under 1.6 bar is not measureable in test.

Figure 2 : Comparative rheological data for old and new LTOBM, PV mPa.s, YP Pa, 600 rpm = Fann 600 rpm dial reading.

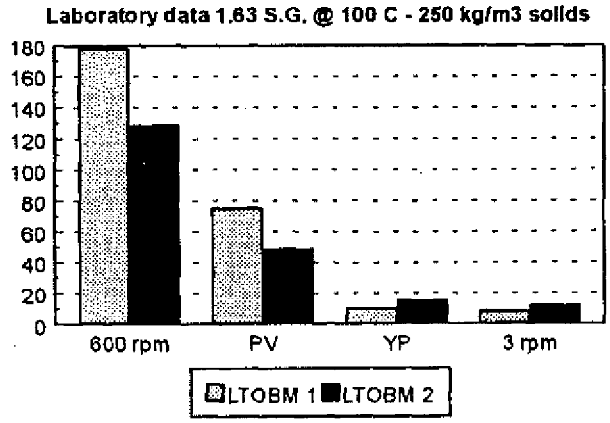


Figure 3 : Shear rate - shear stress curves for the old and new LTOBM's Shear stress = Fann dial reading, shear rate = Fann rpm